The solar dynamo (critical comments on)

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The solar dynamo (critical comments on)

- what observations show
- what they show is **not** the case
- what is known from theory
- interesting open questions

quantitative models ↔ \`figuring things out'

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- clues about deep layers from things happening at the surface
- role of the ‘tachocline’
- dynamo driven by magnetic instability, not ‘convective turbulence’

Things happening on the surface

Tells more about what happens below than realized in most models of the cycle.

- Emergence of active regions: clues to the cycle's workings

- strength and location of the cycle field

- role (?) of convective turbulence

Active region emergence

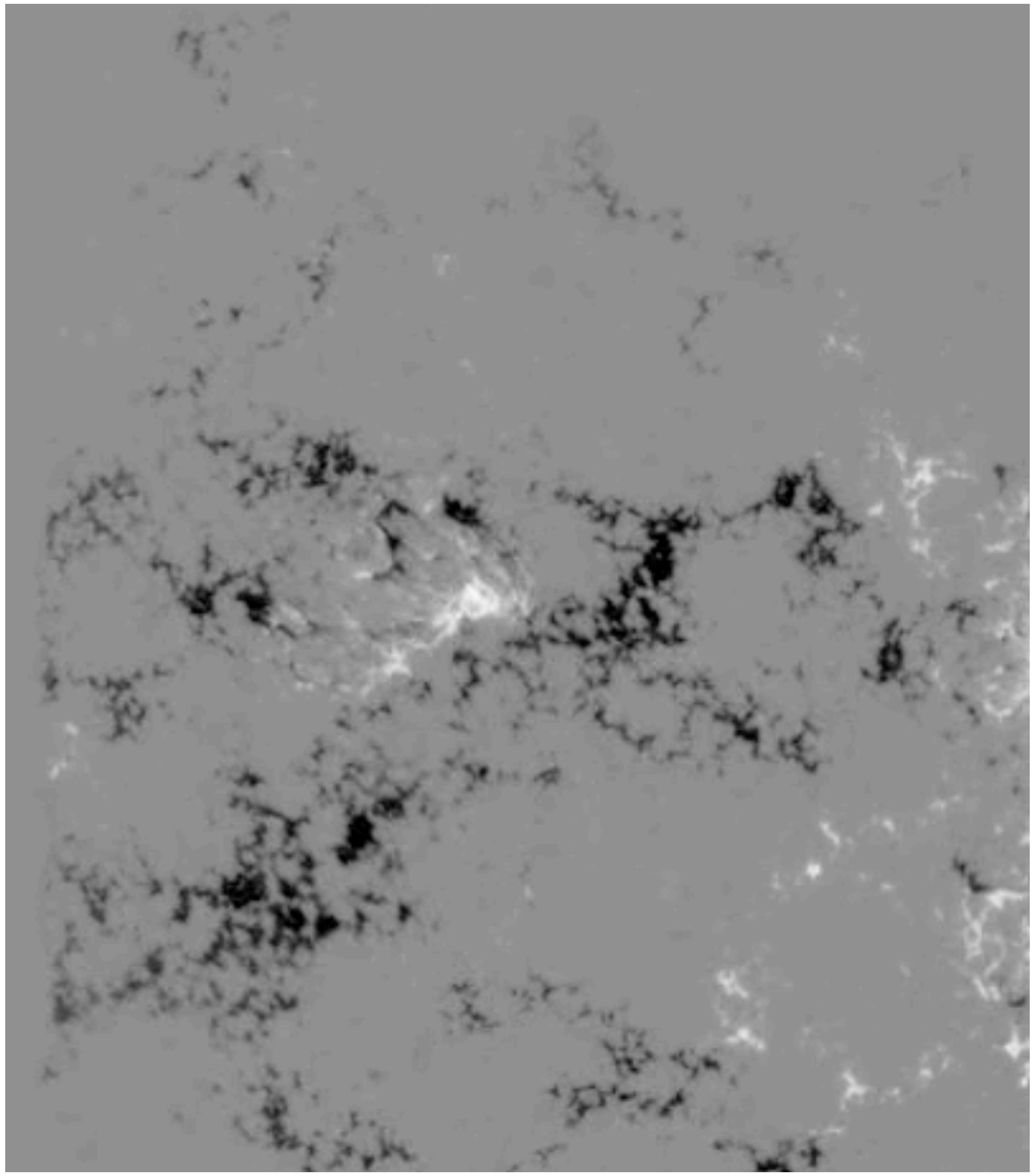
Fields move independent of surface flow.

+,- in opposite directions: `antidiffusion'.

Hinode JAXA/NASA

The Hinode 'trilobite'

Active region emergence



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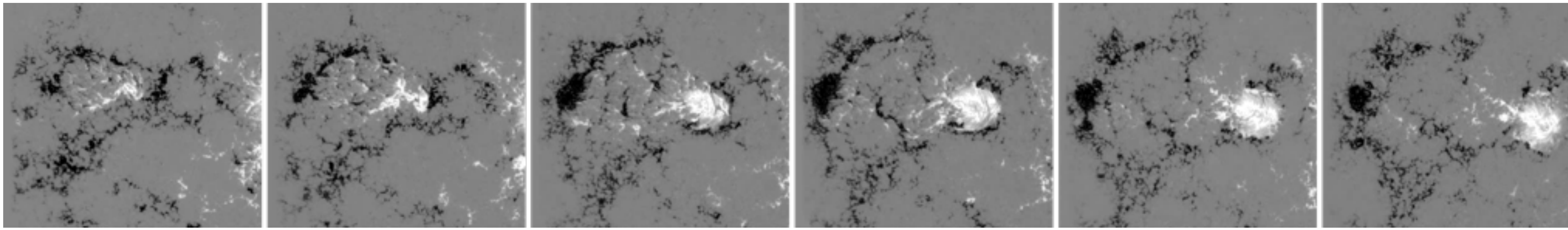


the ‘trilobite’ Hinode JAXA/NASA

Properties

- regularity of Hale’s polarity law
- emerging fields move independent of surface flows (Vrabec 1974), ‘antidiffusion’
- sunspot proper motion time scales - a few days (Herdiwijaya et al. 1997)
- tilt of AR continues to settle after emergence (Howard 1991a)
- mean meridional drift or AR < 0.5 m/s (Howard 1991b)

Interpretation

active region emergence
(Cowling 1953)

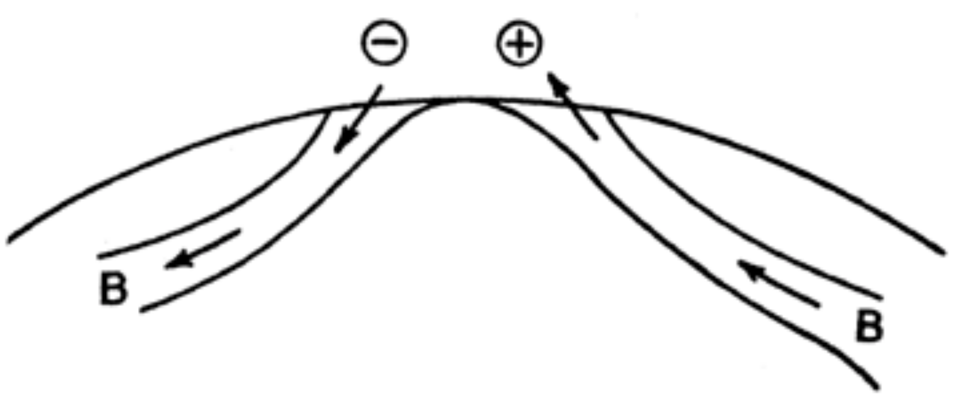
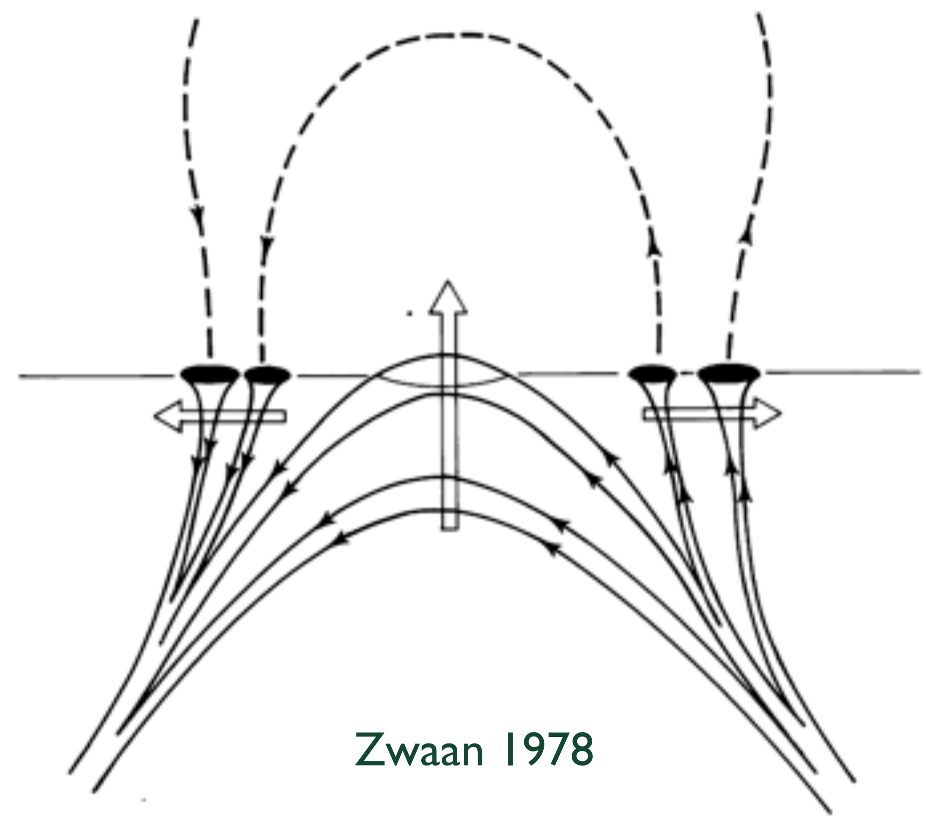


FIG. 5. Showing a strand of the solar toroidal field lifted locally and giving rise to a bipolar sunspot group.

W. Elsaesser 1956

the 'rising tree'



Zwaan 1978

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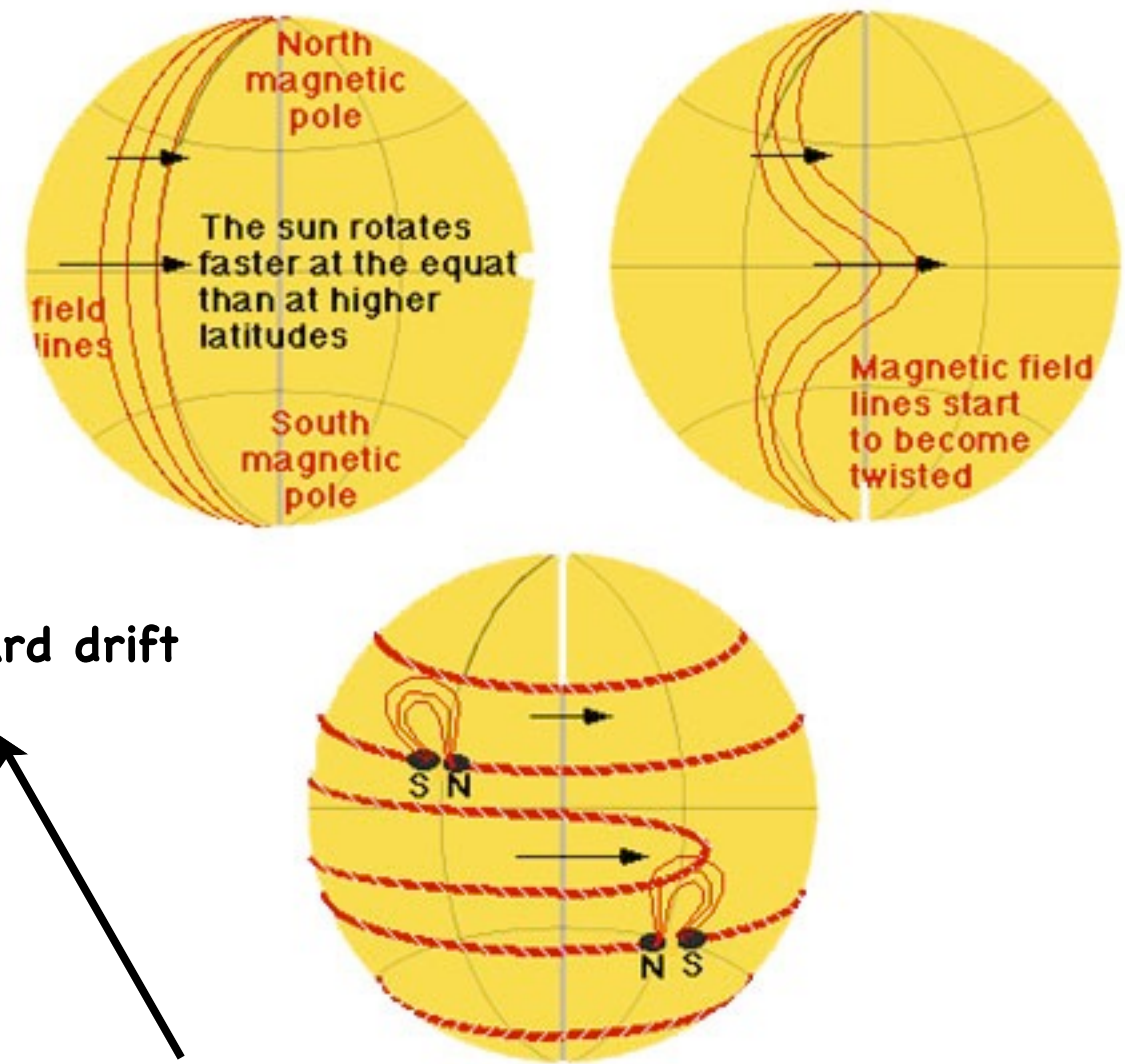
Interpretation (ct.'d)

Q1: why does the field erupt?
A: (Babcock) when its reaches a critical strength

Q2: from which depth?
A: base convection zone.

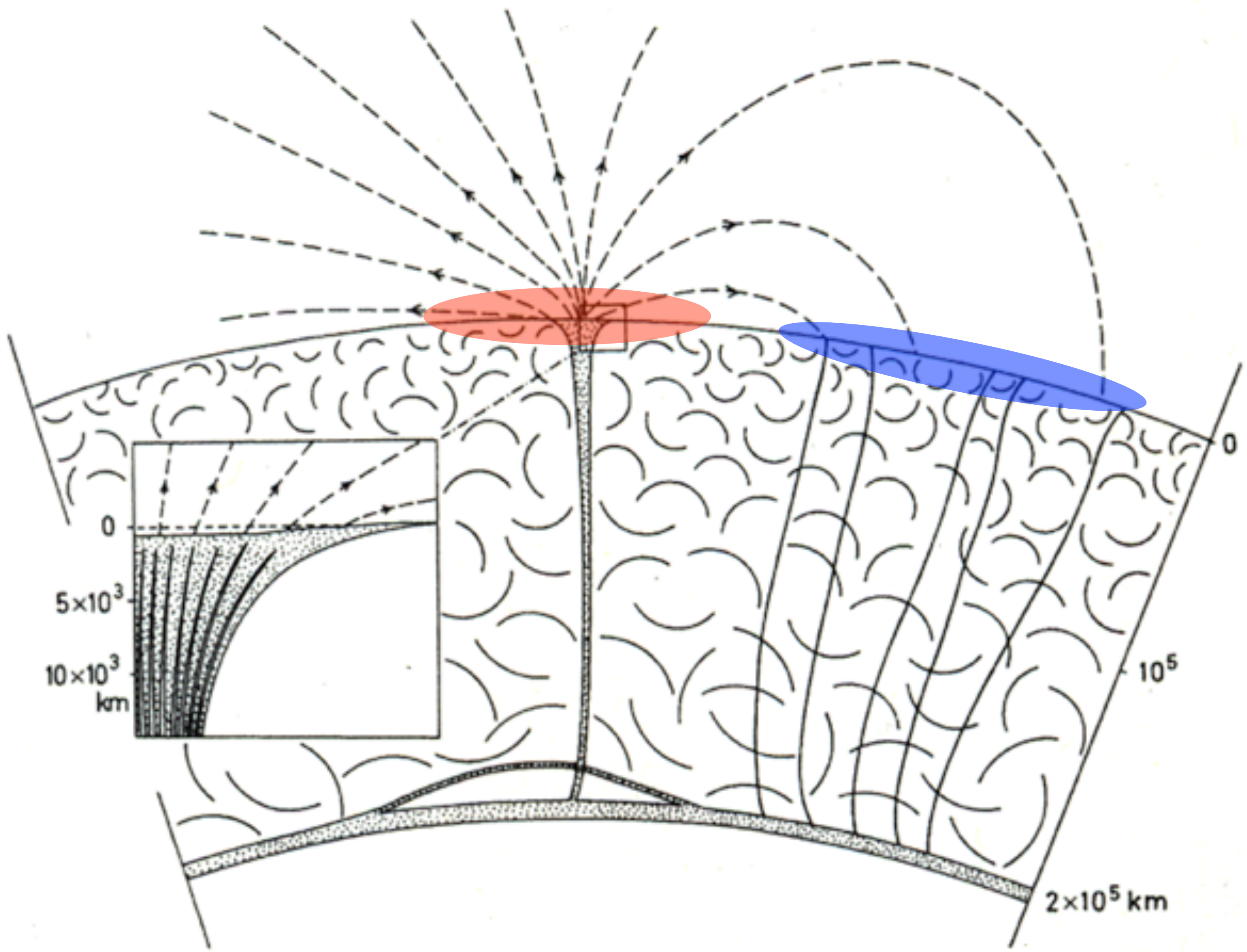
assume for the now, return to in a moment

equatorward drift



'Winding-up' by differential rotation with **latitude**

Interpretation (ct.'d)



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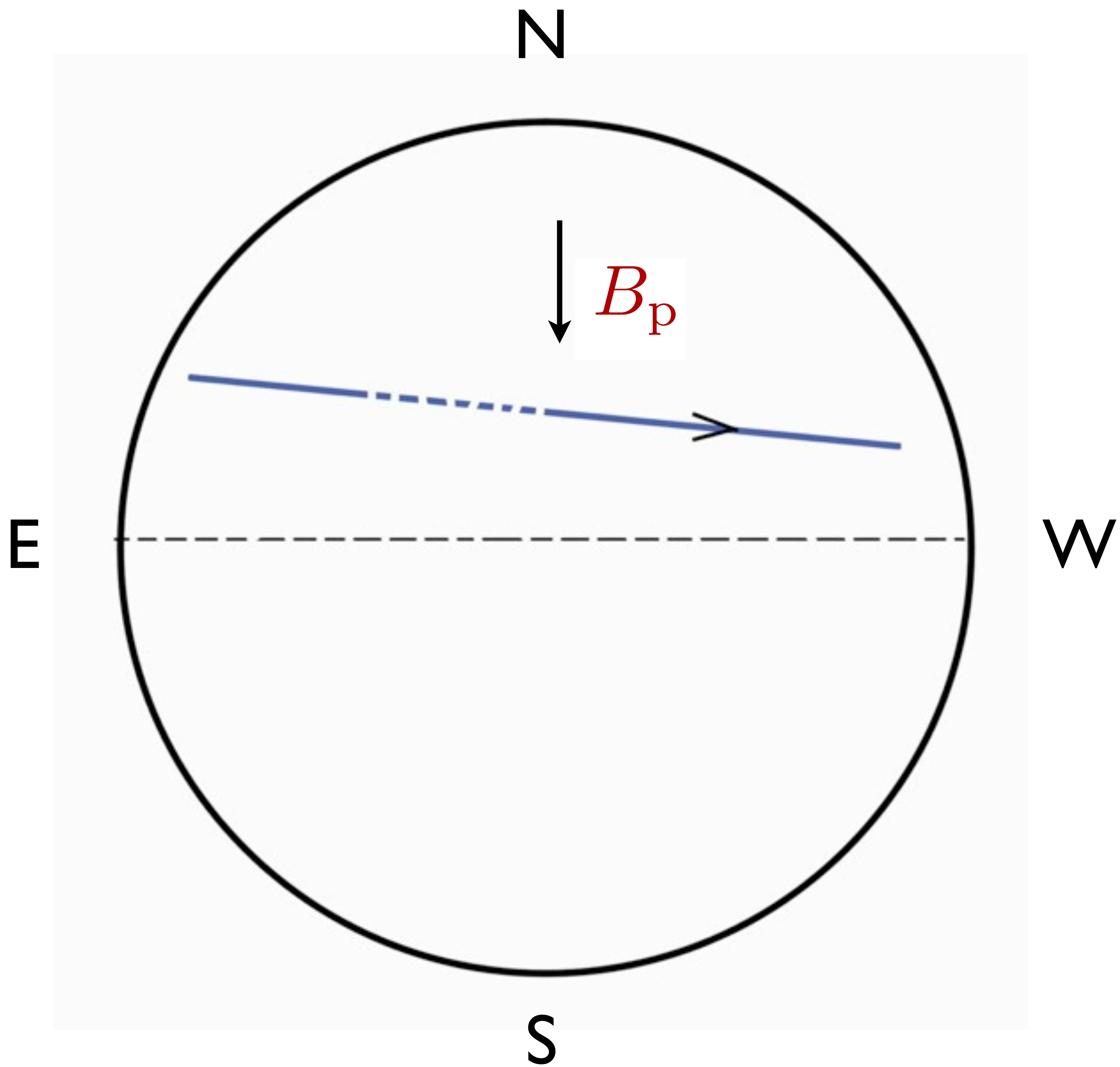

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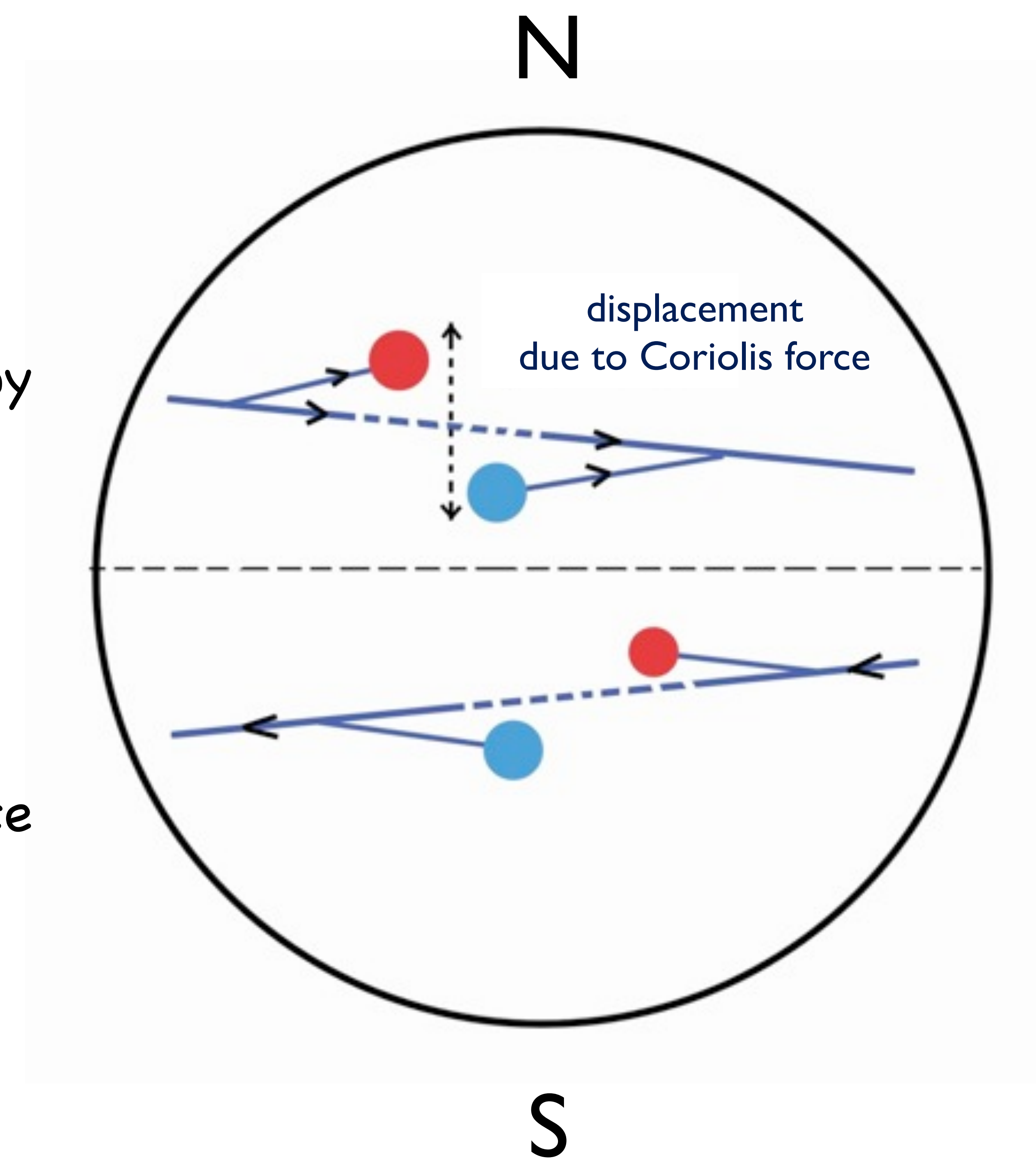
Interpretation (ct.'d)

- active region tilt produced by emergence is the 'α-effect' of the cycle

(H.W. Babcock 1961, R.B. Leighton 1969)

Q: which flows (where) produce the Coriolis displacement?
A: look at tilt development



Q: where is the tilt produced?

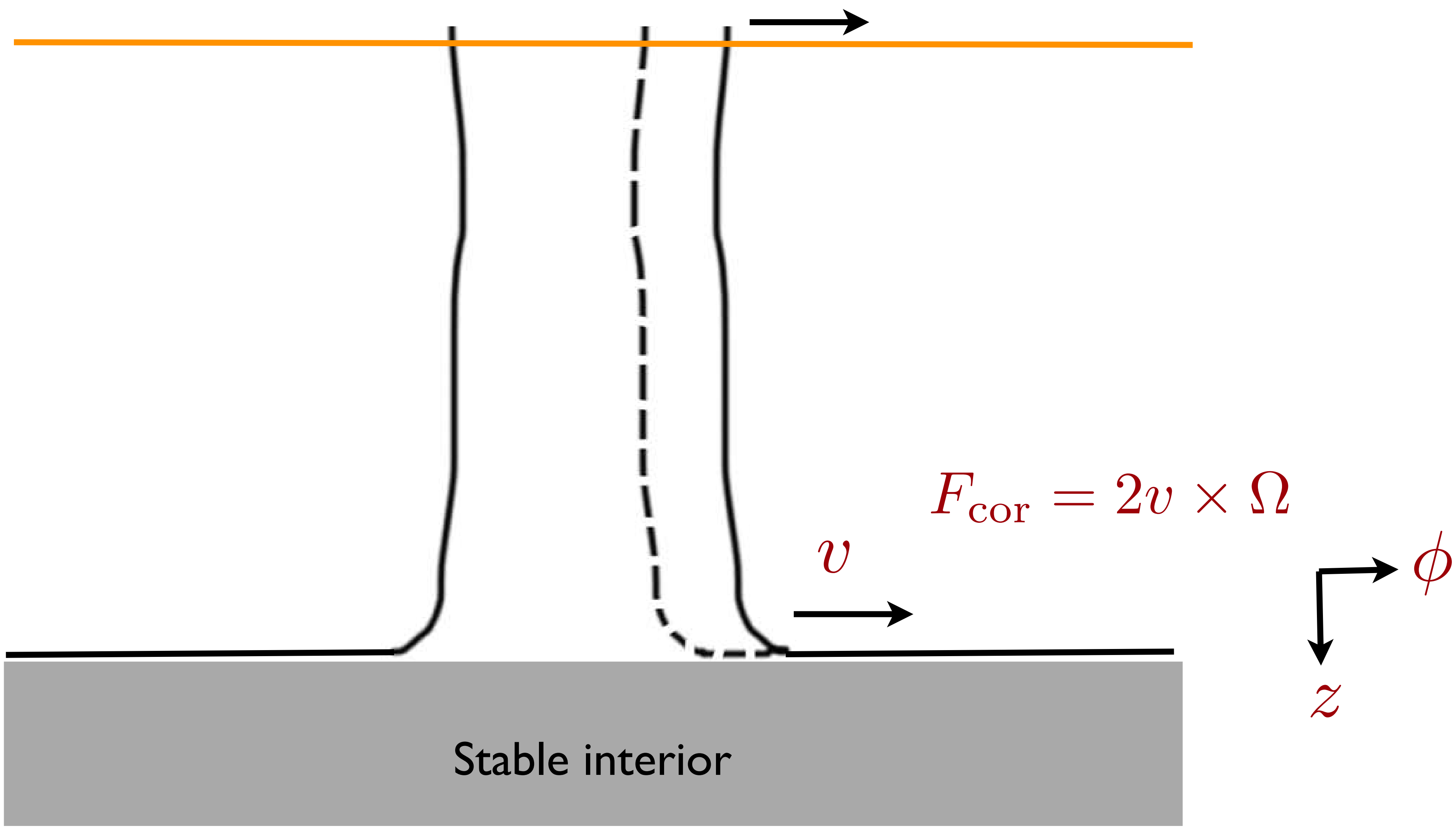
look at tilt development (Howard 1992)

- most tilt **after** main flux emergence,
- during separation of polarities

Effect is **not** caused at the surface

- mass (ρ) energy density (B^2, P) is at the **base**

Coriolis force on spreading AR



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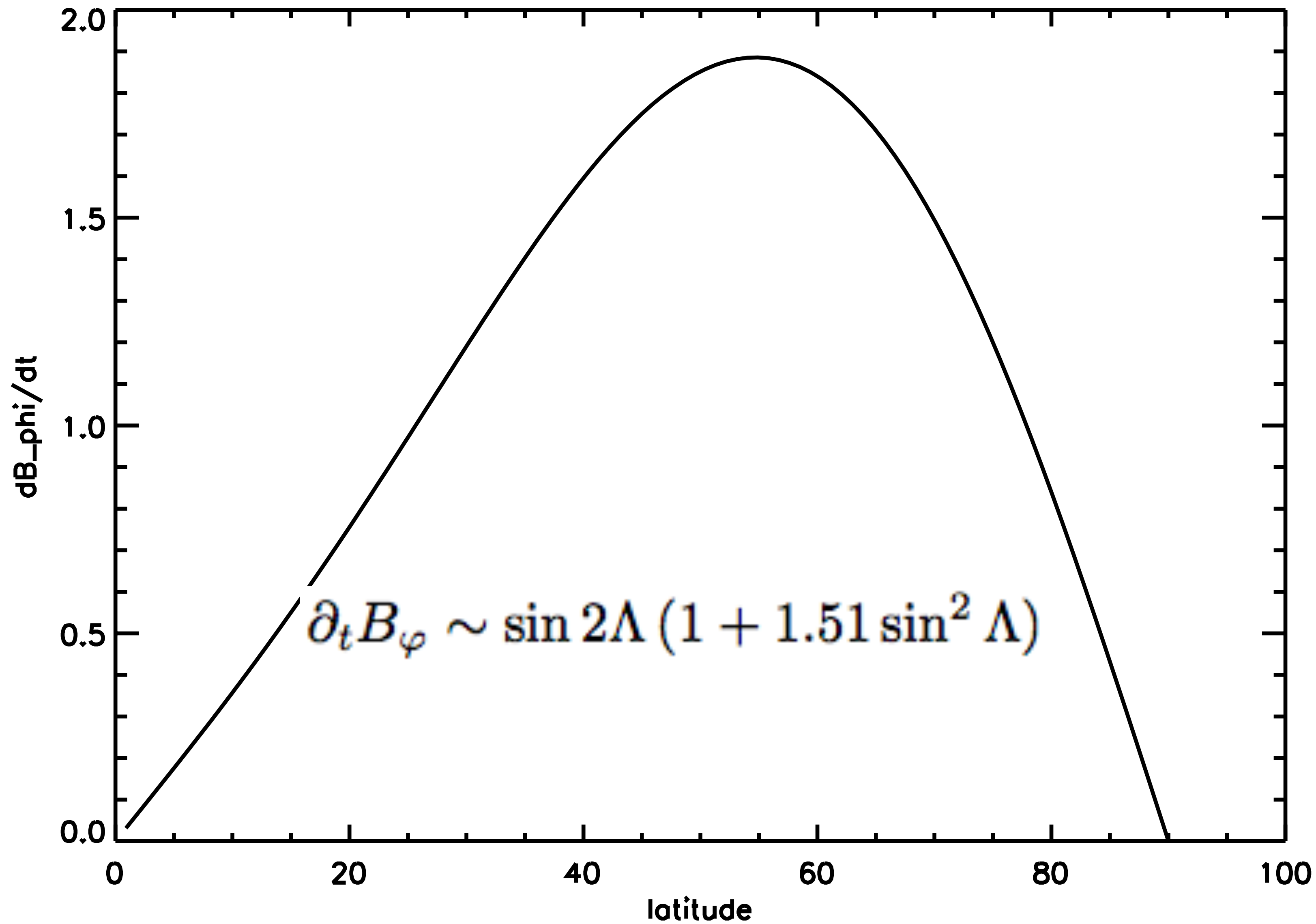
Equatorward drift (Babcock 1961)



$B_{\rm inst} \sim 10^5\,{\rm G}$ (Schüssler et al. 1994)

Equatorward drift+‘Polar branch’

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Questions:

- location
- strength

$\Big\}$ of the azimuthal field

Location?

Field of 3000G (spots @ surface) is *buoyant.*

buoyant rise time $z/v_{\rm A}$ = 2d (z=50 Mm)

➔ spots are 'anchored' deeper than 50 Mm

➔ they are not a surface effect

Magnetic buoyancy can be compensated by lower temperature
Buyoant (Parker-)instability
Convection zone itself unstable $\Big\} \rightarrow$

stable location: base of the convection zone

Field strength?

Rising flux tubes: 1D simulations

Choudhuri & d'Silva 1993,
Fan & Fisher 1994
Schüssler et al. 1994

Model for fields rising from base of the CZ
- 1D: flows along and across tube
- including thermal and magnetic buoyancy
- free parameter: B at base

data to fit:
- latitude of emergence
- time scale
- AR tilt

convergence with these three obs. for $B \sim 100\,\mathrm{kG}$

➔ $$\frac{B^2}{2\pi} >> \frac{1}{2}\rho v_{\mathrm{conv}}^2$$

➔ emergence process only weakly influenced by convection

Interpretation (ct.'d)

Why at base CZ?
- field is not passively carried by flow → stronger than equipartion
- stratification of convection zone has no restoring forces
- fields can not 'float midway' for as long as years
- floats to top or sinks to bottom (if heavy enough ...)

--> winding-up during cycle must happening @ base

- **If** at base CZ:

- field becomes unstable (Parker instab.) at $\approx 10^5\ \mathrm{G}$ (Schüssler et al. 1994)

'rising tube' simulations:
- rise time $\approx$ days
- in the observed latitude range
- with right AR tilt

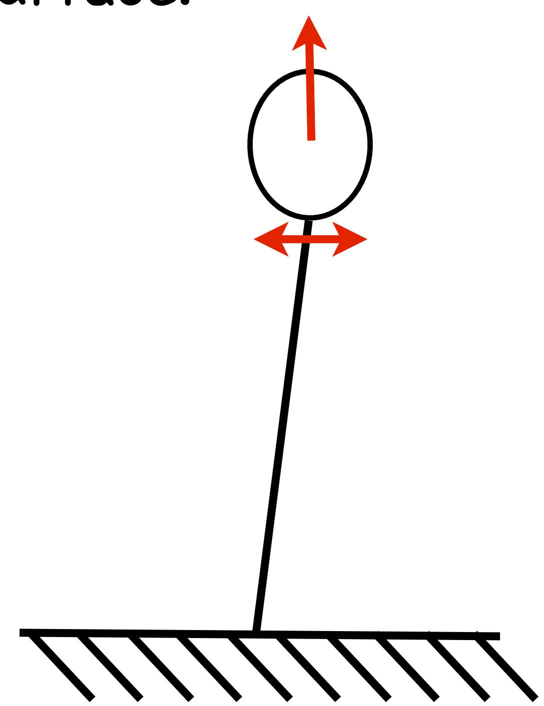
(Choudhuri & D'Silva, Caligari etal, Fan & Fischer)

Interpretation (ct.'d)

-> contact made between MHD of interior and observations @ surface.

Explains:

- Hale's & Joy's laws
- time scale of spot proper motions (Alfvén travel time)



'Tethered balloon'

consequences:

- Field is stronger than convection
- → direct connection between surface and interior
- B not generated by `interaction with turbulent convection': cycle operates on differential rotation and instability of B. (compare: field generation in accretion disks)
- Differential rotation with latitude (not radius)

Theories

- turbulent mean field models
- superficial sunspots
- flux transport models

traditional models

The need to produce quantitative models

- mean field alfa-omega:
  - interaction turbulent convection - magnetic field
  - kinematic
  - operating in bulk of CZ

variations:

- tachocline dynamos
- flux transport dynamos

mean field electrodynamic models
convective dynamo models

Responds to the need for quantitative, computable models

Little or no *contact with observations*:
- inconsistent with emergence process, sunspot formation
- kinematic.

assumptions:
- Active regions are 'turbulence' ('to be averaged out')
- Field strength dictated by interaction w. convection
  (contradicted by strength of sunspots)
- Takes place by interaction between convection and B
  (contradicted by phenomenology of AR emergence)

predictions
- rotation rate depends more on depth than latitude
  (contradicted by helioseismology)

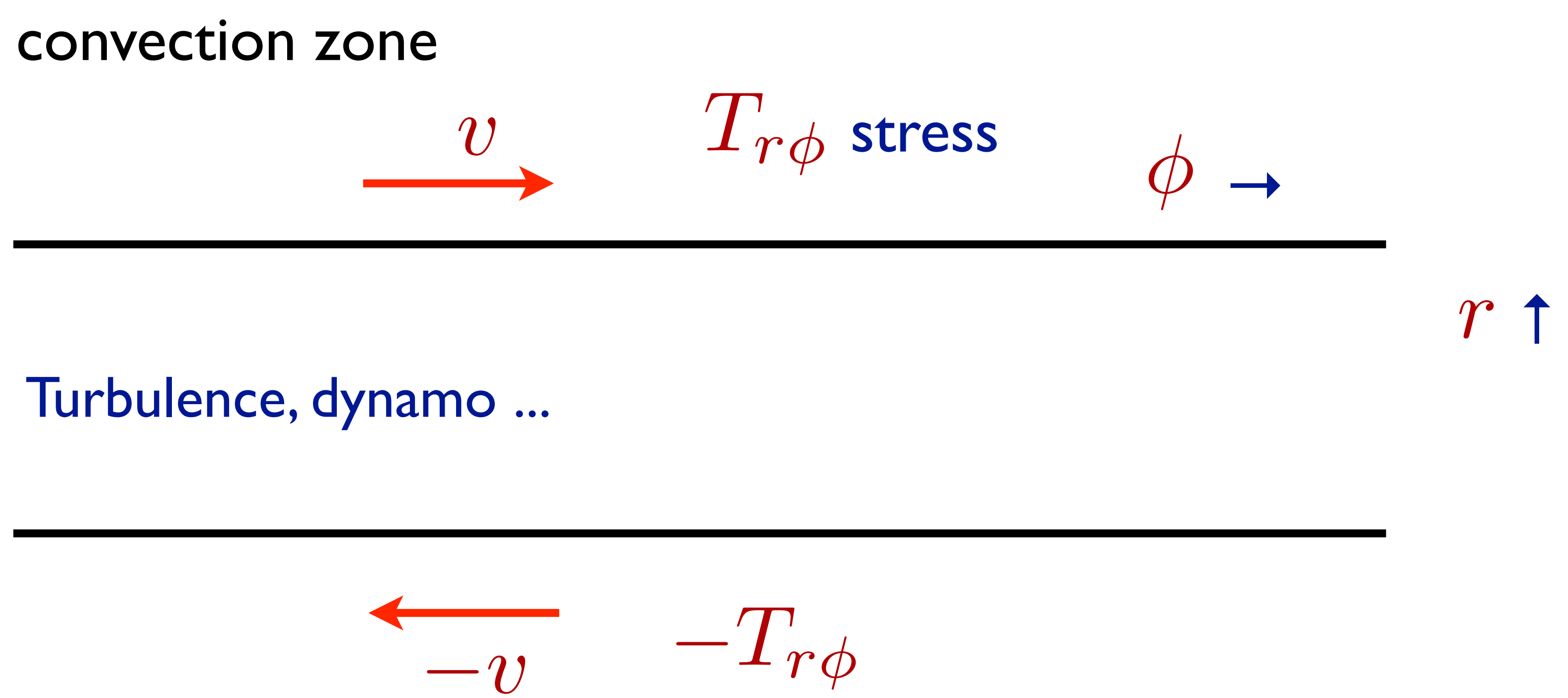
theoretical justification
- high $\mathrm{R_m}$: B *intrinsically non-local* (↔ scale separation)

Tachocline dynamos

1. Why the tachocline is not what operates the solar cycle

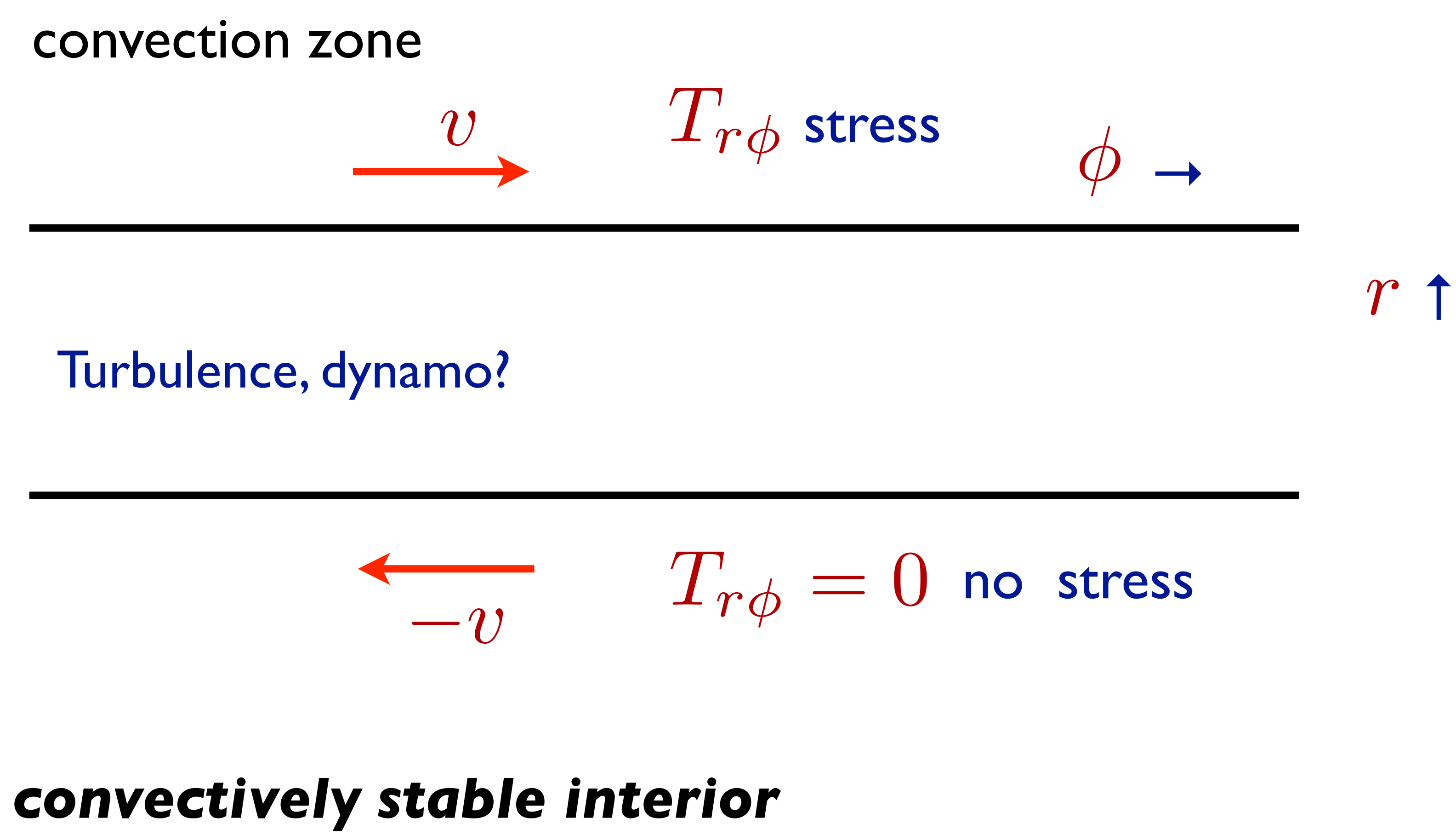
‘Tachocline’ $\leftrightarrow$ ‘base of convection zone’ (not same thing)

- radial shear in CZ predicted by convective mean field electrodynamics absent,
- shear is in latitude
- move dynamo into tachocline?



'shear between moving plates'

- radial shear in CZ predicted by convective mean field absent
- shear is in latitude
- move dynamo into tachocline?



convection zone,

Re stress $< v_r v_\phi > \;\; \rightarrow \nu_\mathrm{t} \sim 10^{13}\ \mathrm{cm}^2/s$

$v \longrightarrow$ $\quad T_{r\phi}$ stress $\quad \phi \rightarrow$

$r \uparrow$

Turbulence, dynamo?

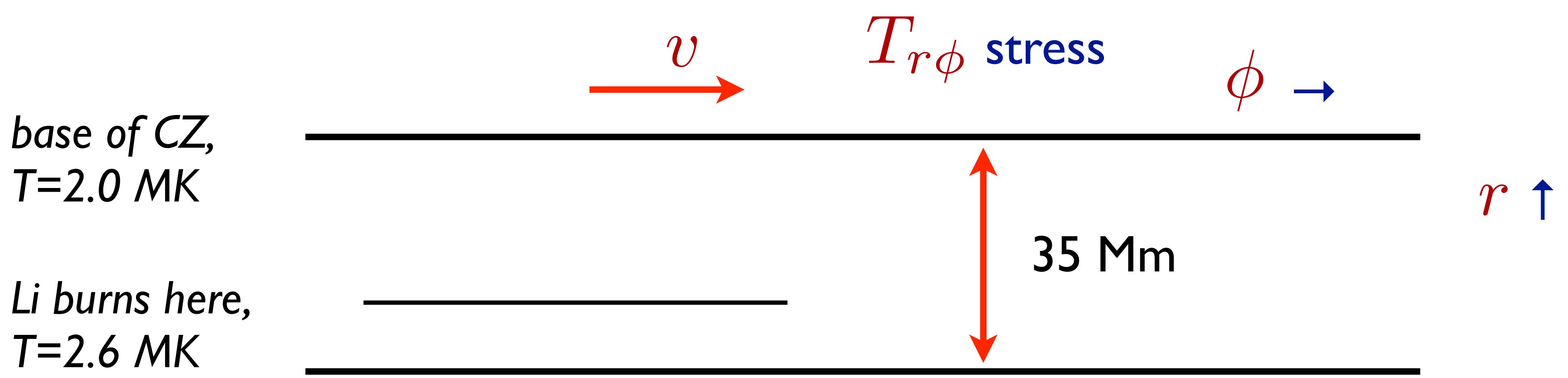
$\longleftarrow -v$ $\quad T_{r\phi} = 0$ no stress

convectively stable interior: $\nu \sim 10\ \mathrm{cm}^2/\mathrm{s}$

viscous stress vanishes

convection zone,

$$\mathrm{Re}\ \text{stress}\ < v_r v_\phi > \ \rightarrow \nu_{\mathrm{t}} \sim 10^{13}\ \mathrm{cm}^2/s$$



$$\nu \sim 10^3\ \mathrm{cm}^2/\mathrm{s}$$

↑ from *Li - depletion constraint*

Q:

1. What causes the thin tachocline?
2. What operates the solar cycle?

A:

1: Tachocline is an imprint of the latitudinal differential rotation into the interior. (Spiegel & Zahn 1992, McIntyre 2007)

2: $\Omega(\theta)$

Consequences for all models that use $\Omega(r)$.

flux transport dynamos

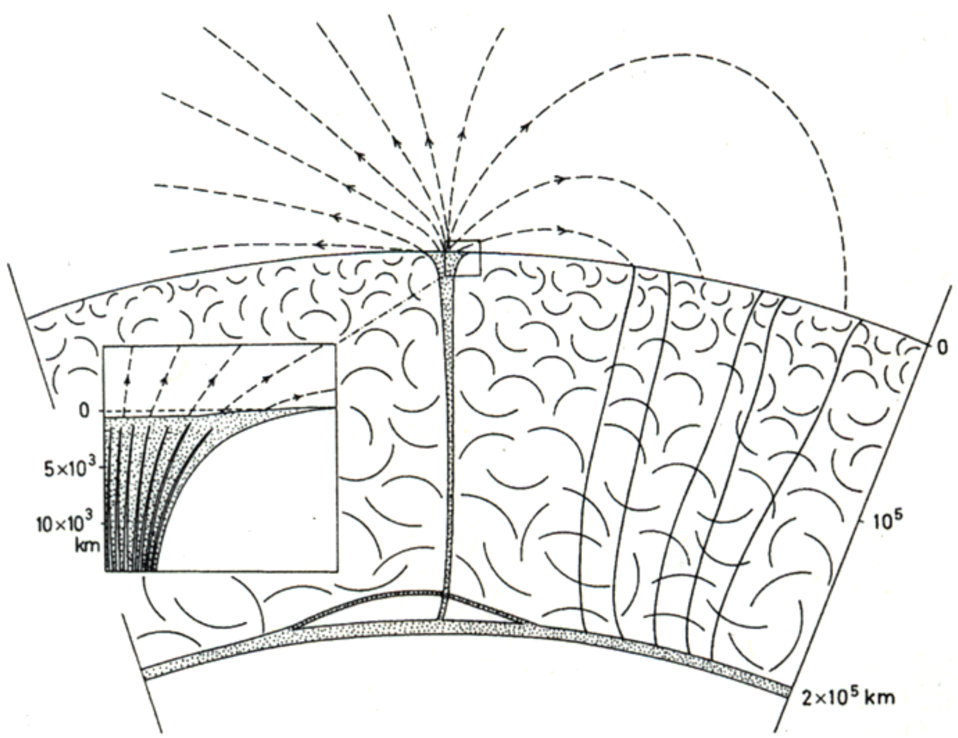
- mean field alfa-omega equations (kinematic …)
- sources of alfa-effect at surface (observational illusion …)
- flux transport at surface (”)
- latitude drift of active zone by return flow (not observed …)

Solar cycle: open issues

1 'Thermodynamic problem':
strength of the field @base requires low temperatures

$$B = 10^5 \hat{=} \delta T/T \sim 10^{-4}$$

2 Flux disappearance rate (Labonte & Howard 81: AR flux lives 10d)



- turbulent diffusion: not an explanation.
- reconnection: where?

(c.f. Parker 2009)

Flux disappearance rate: how long does the flux of the cycle stay around?

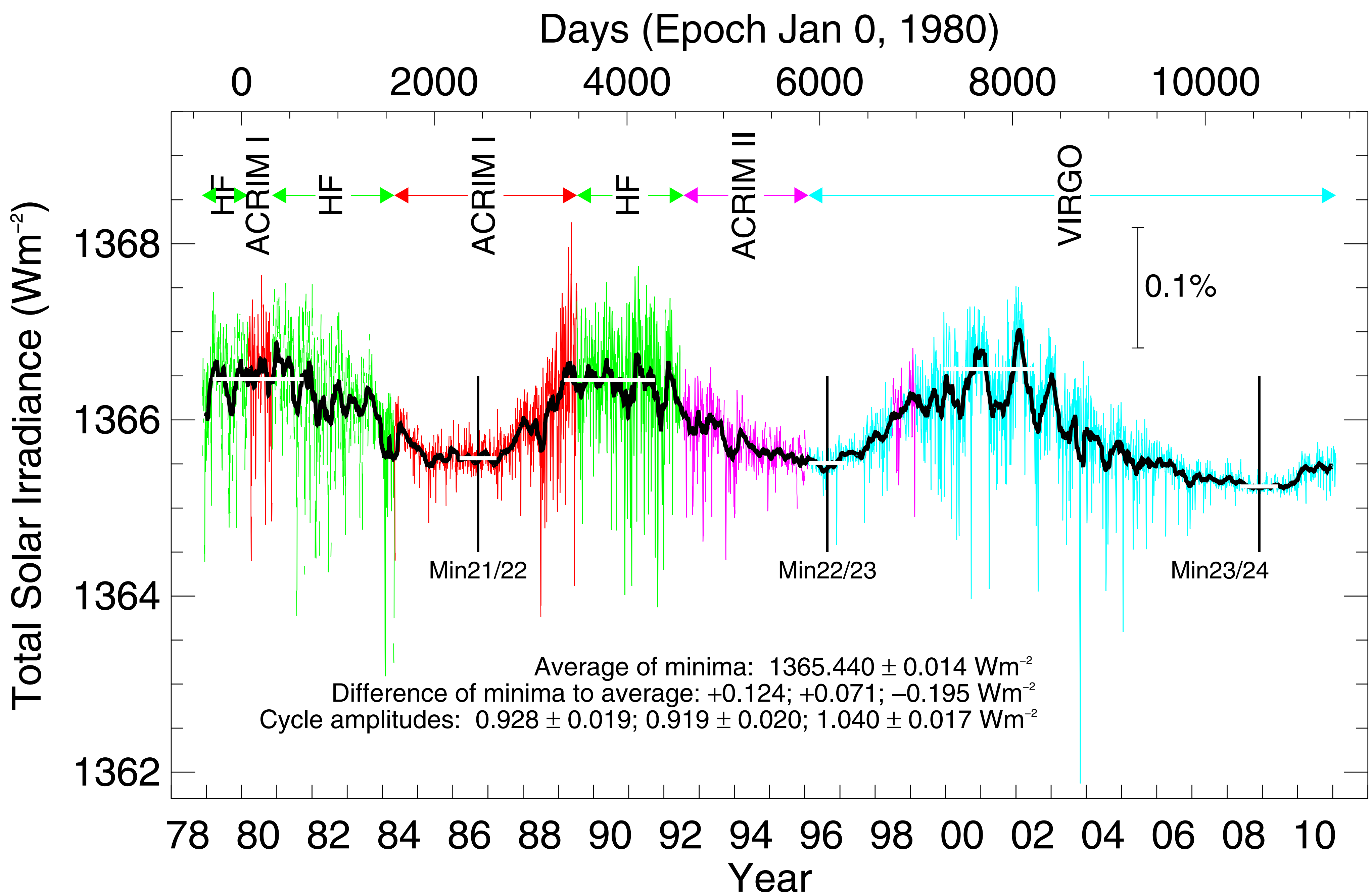
- TSI decline during last (extended) minimum
- how much does the quiet Sun magnetic flux contribute to TSI?

Magnetic brightening of the Sun

'quiet Sun' : $\langle|B_z|\rangle \approx 10\,\mathrm{G}$

Q: - dependence on cycle phase?
- effect on brightness?
- long term variation?

Magnetic brightening of the Sun



C. Fröhlich et al. 2011

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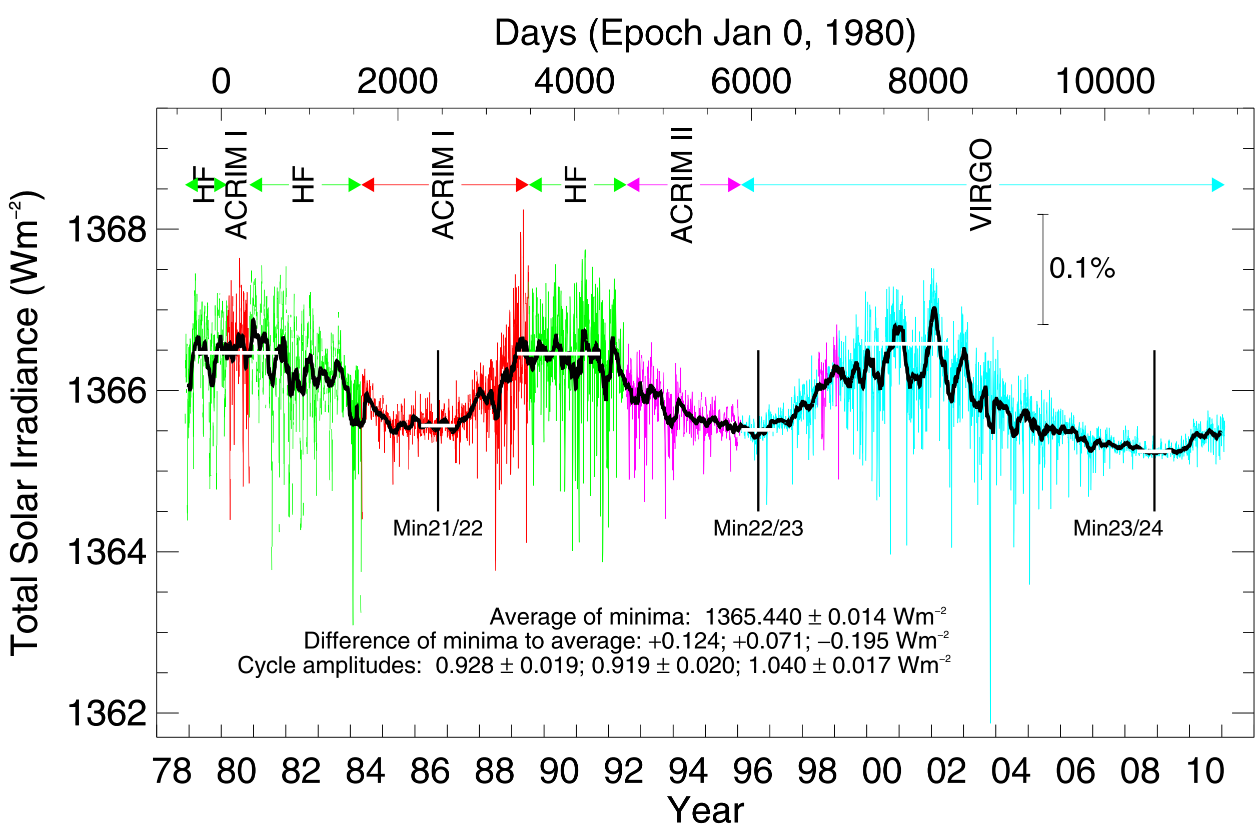
Magnetic brightening of the Sun

- brightness of small scale field dominates over spot darkening
- 0.08% cycle variation of TSI has no climate effect

- possibly larger longer term variations?
  * magnetic fields
  * as yet unknown mechanisms



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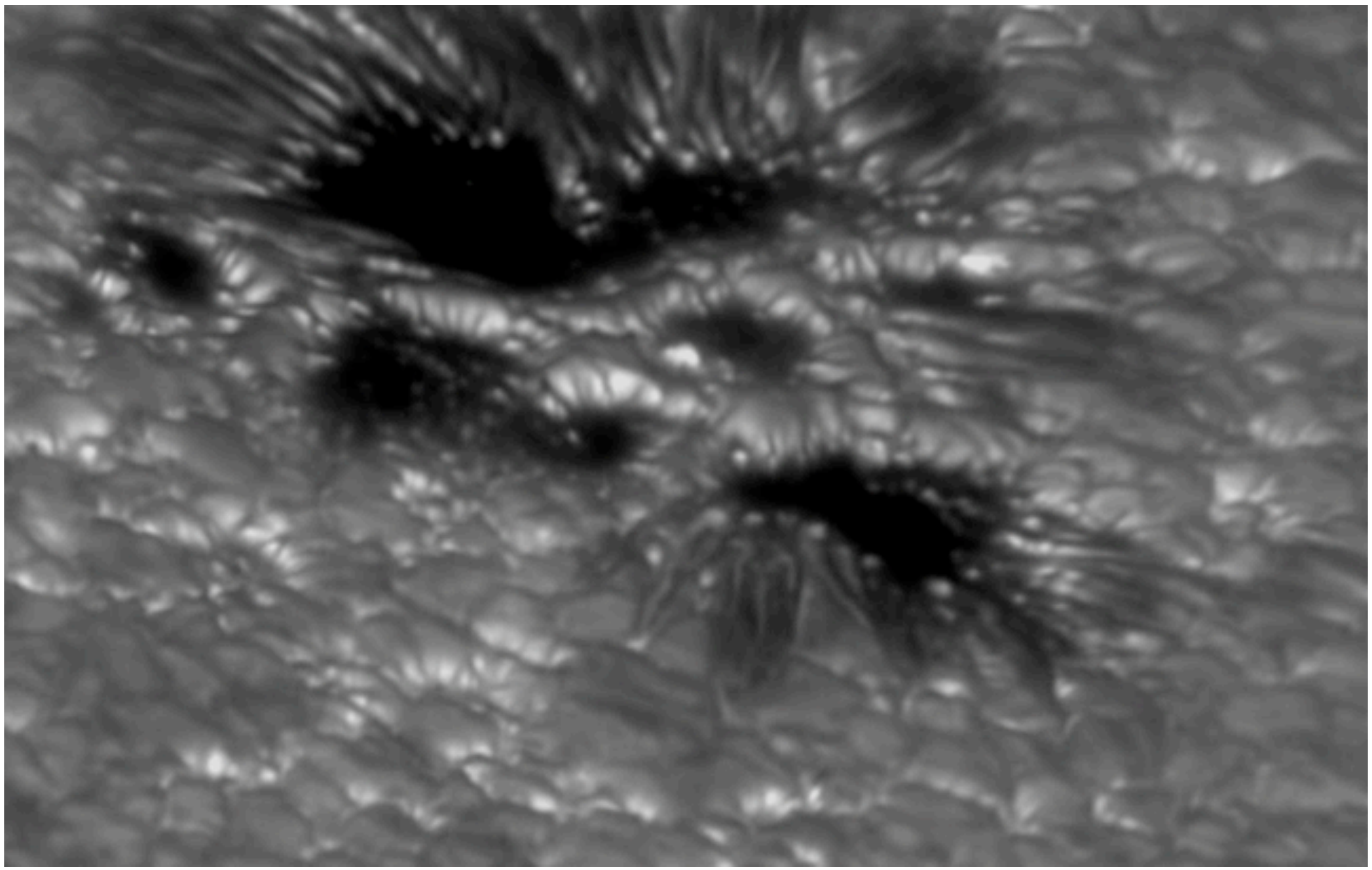
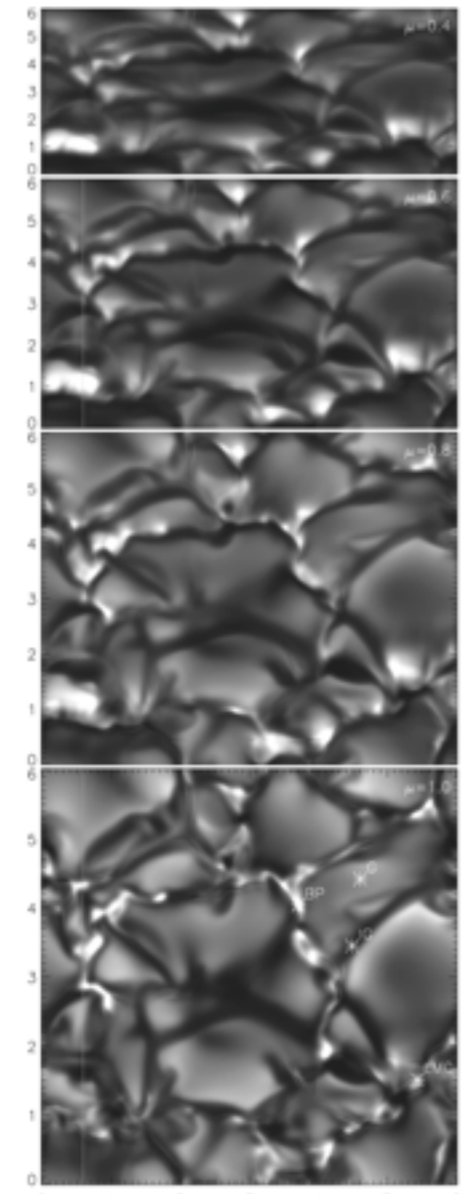
Magnetic brightening of the Sun

'bright wall effect' :



SST



simulation

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Magnetic brightening of the Sun

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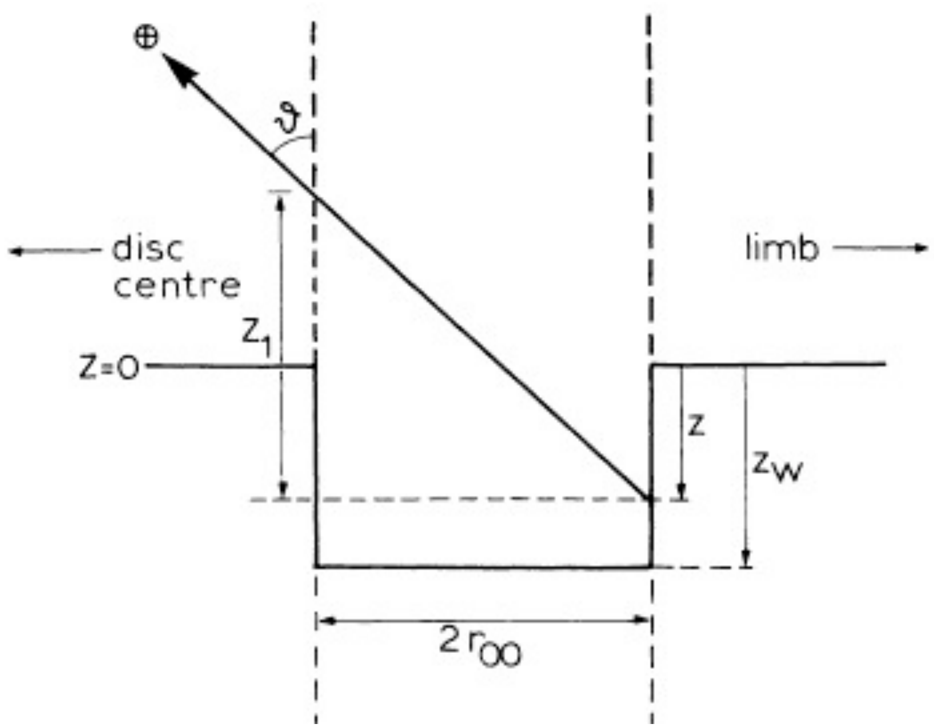

- small scale field causes heat leaks in surface HCS 1977

→ enhanced cooling

→ geostrophic flows around AR → 'torsional oscillation' HCS 2003

Magnetic brightening of the Sun

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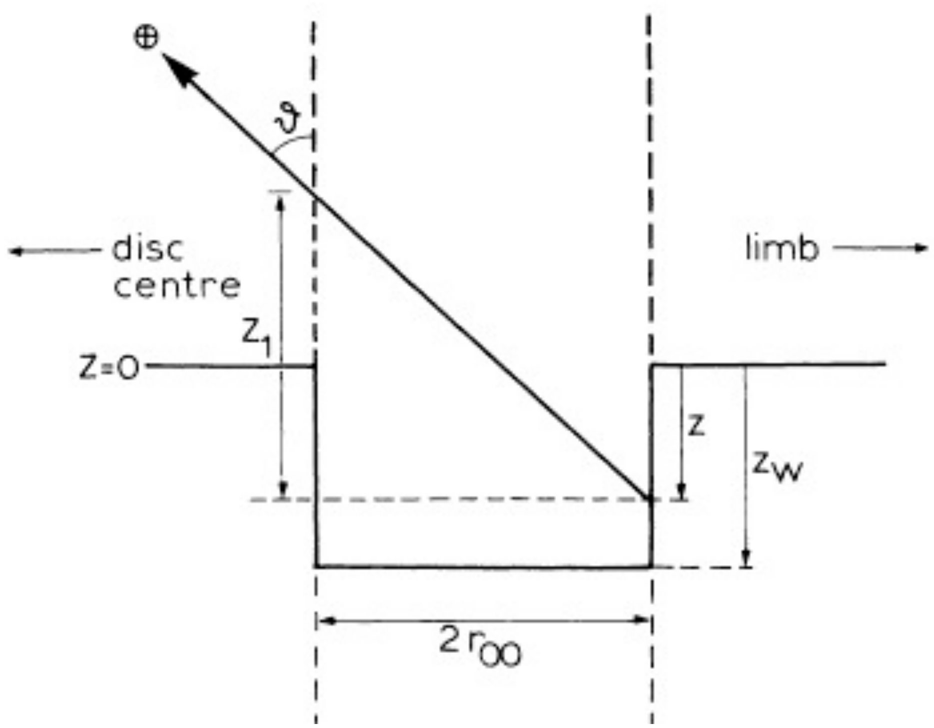

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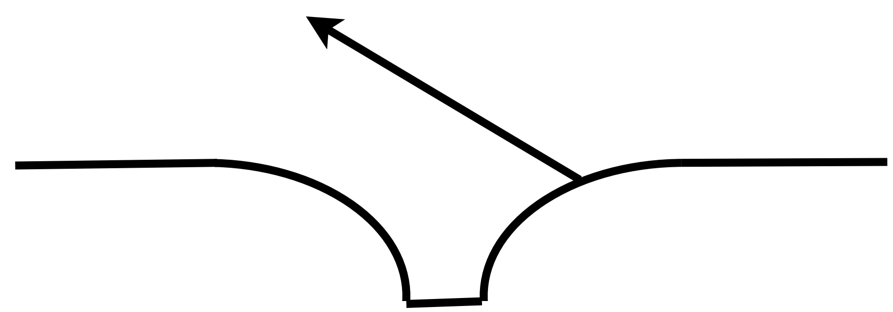


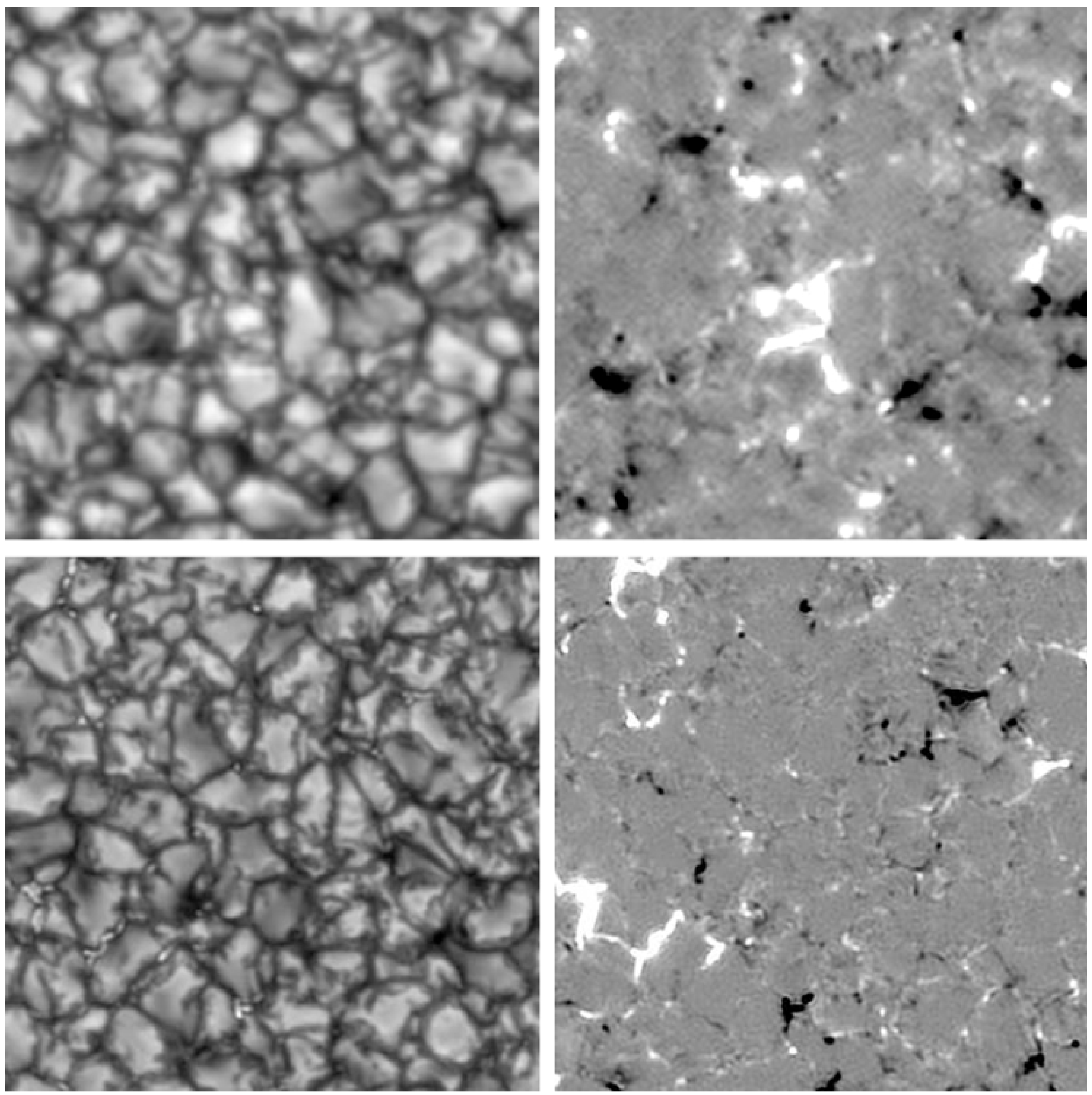
important epicycle

most of the brightening effect due to the 'curved rims'
Steiner 2005, Carlsson et al. 2004

Measuring magnetic brightening of the Sun

R. Schnerr & HCS, 2011

I_630 B_z



Hinode $\delta I_{\mathrm{mag}}/I = 1.2\,10^{-3}$

<|B_z|>=11 G

SST $\delta I_{\mathrm{mag}}/I = 1.5\,10^{-3}$

<|B_z|>=10 G

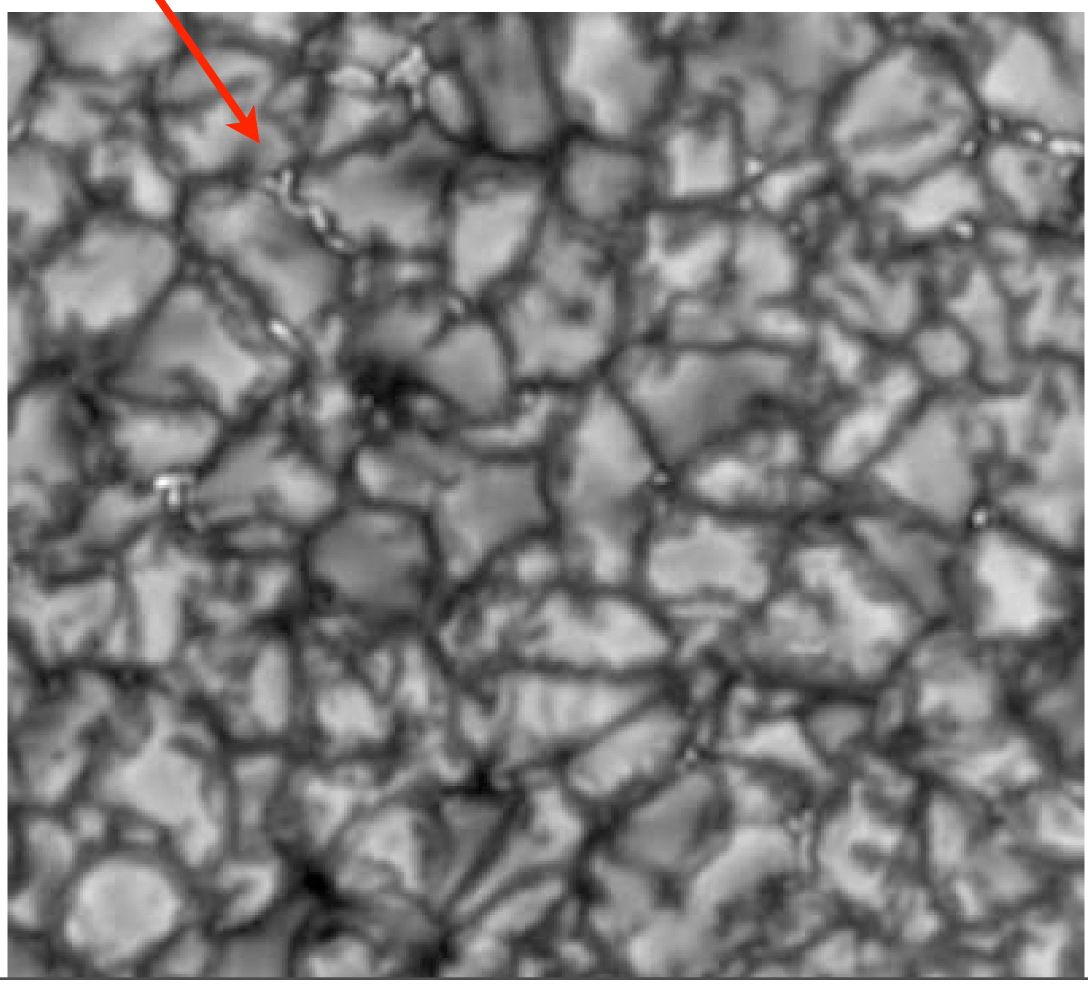
relation with `inner network' fields
(Livingston & Harvey 1975, S. Martin)

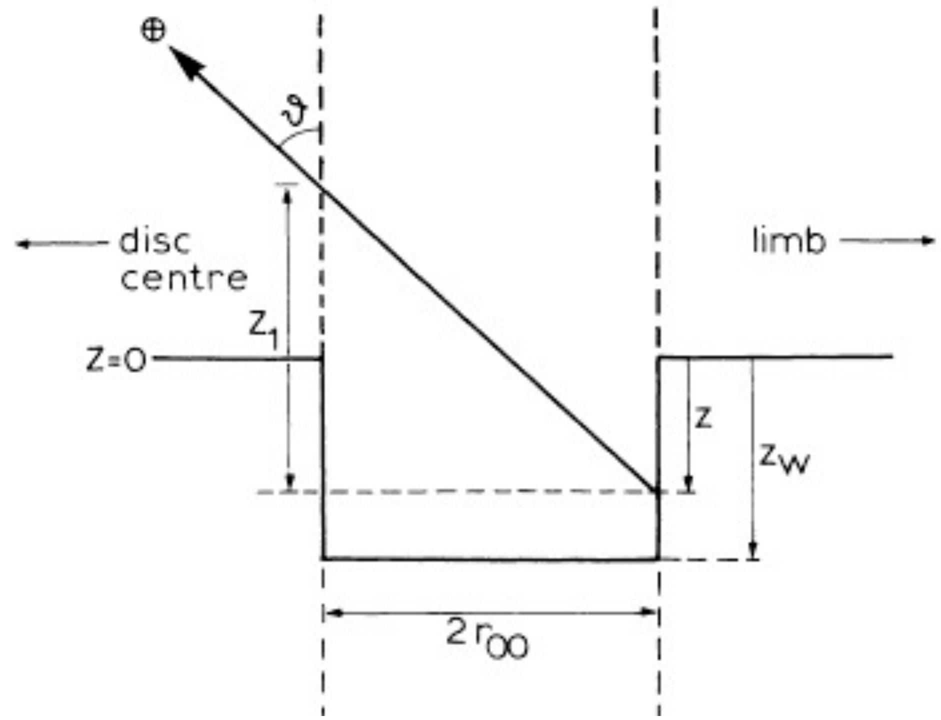
disk center

measured (disk center): $\delta I_{\rm mag} \approx 1.5\,10^{-3}$ $\quad (\langle B_z \rangle = 10\,\mathrm{G})$

does not include:

- dark rims (compensation)
- effect on surrounding granulation ??





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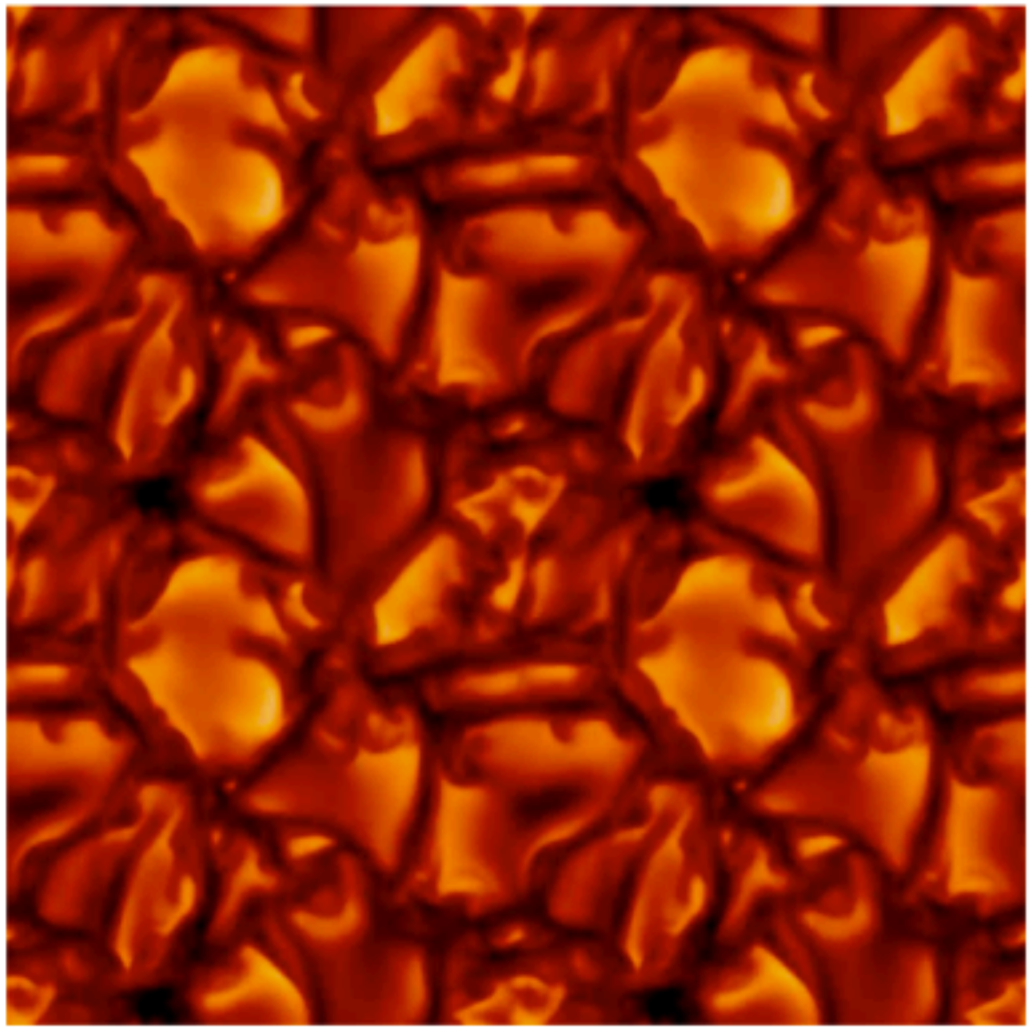
Measuring magnetic brightening with numerical simulations

Bolometric flux $< B_z >= 50\,\mathrm{G}$ B_z



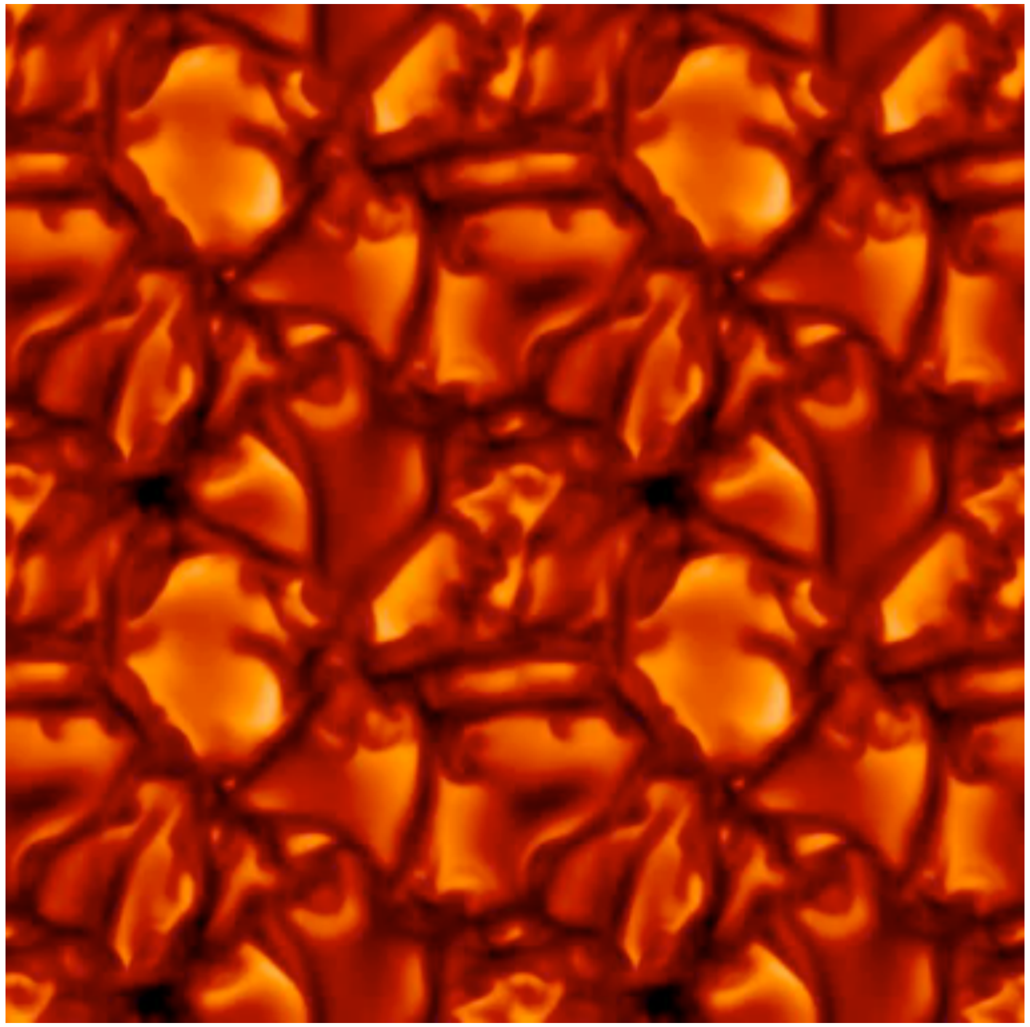
Irina Thaler & Remo Collet @ MPA

Measuring magnetic brightening with numerical simulations

Bolometric flux

$< B_z >= 50\,\mathrm{G}$

B_z



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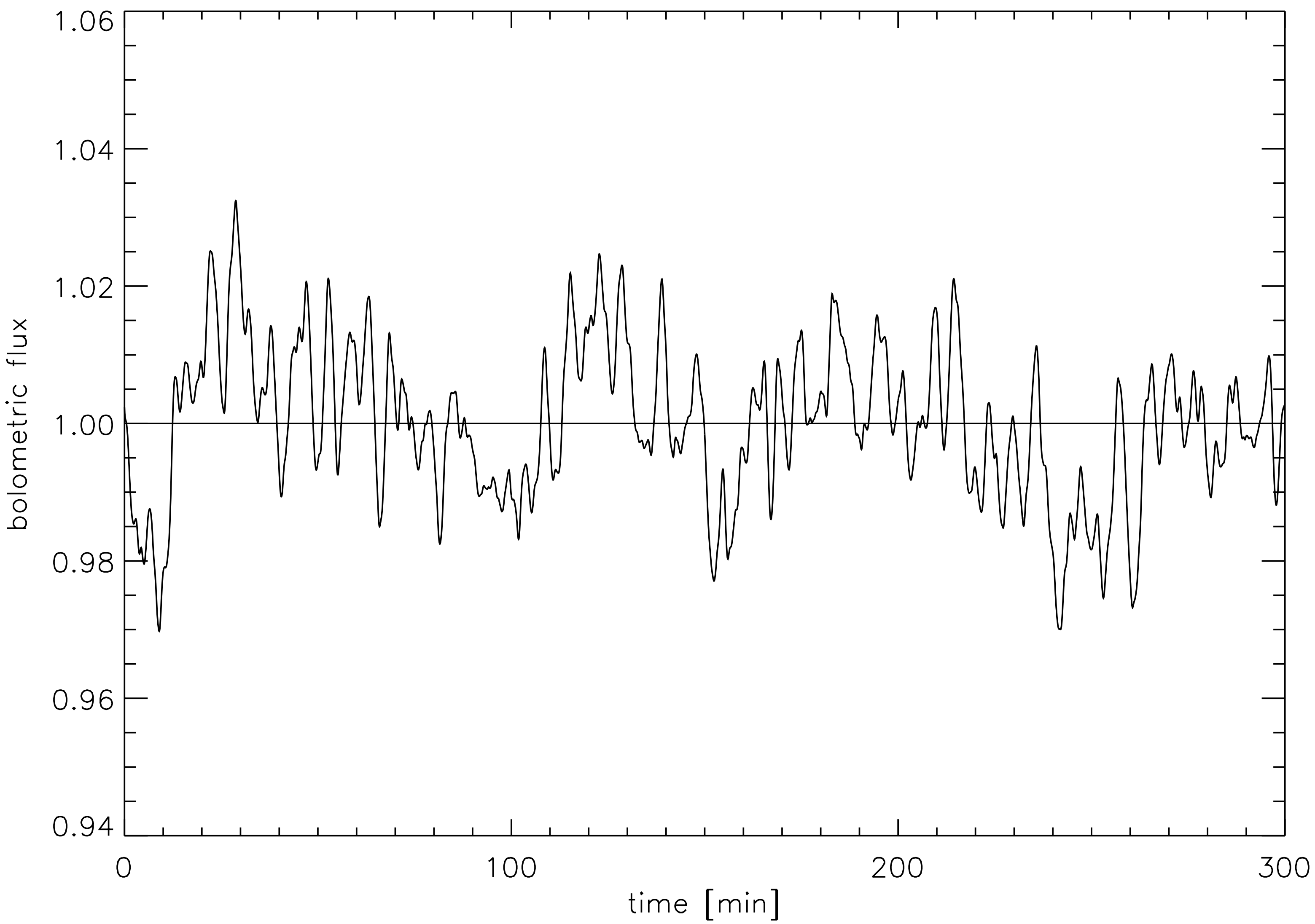
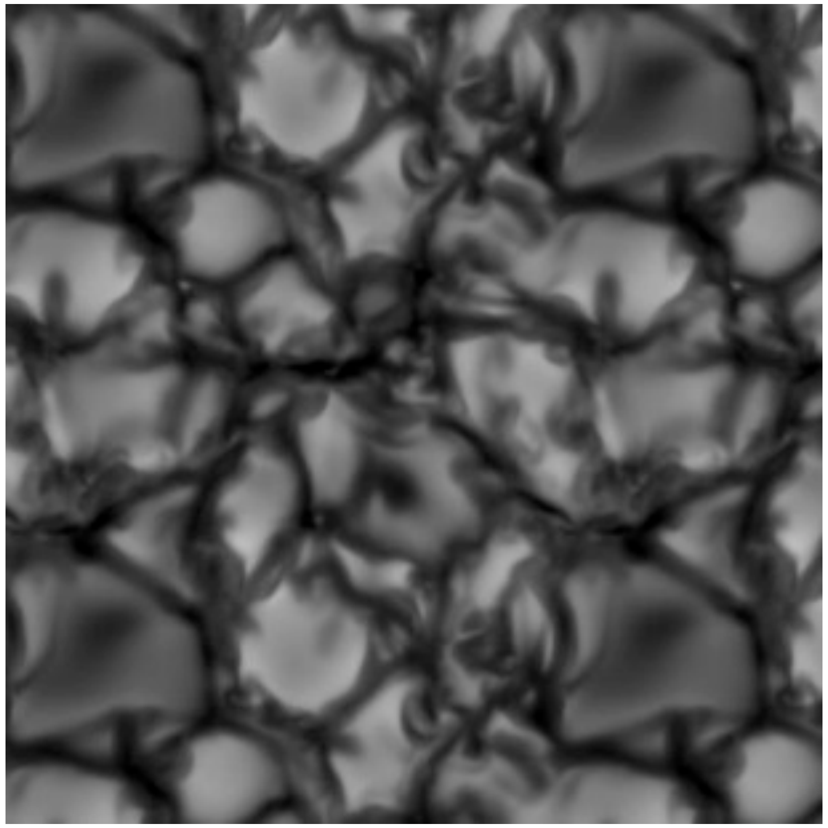
Opposite polarities develop. Inner network field? (Livingston & Harvey 1975)
'surface dynamo'? (Schüssler et al. 2007)

Granulation (B=0, 6x6 Mm)





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result (preliminary):

$$\langle B_z \rangle = 50\,\mathrm{G} \rightarrow \delta F / F_{\mathrm{bolometric}} < 0.5\%$$

Q: - cycle dependence?
- is the background field a 'local dynamo'?

Summary

- solar dynamo is not kinematic.
- it operates on differential rotation and magnetic instability, not convective turbulence.
- underappreciated observational clues in existing observations of AR.
- cycle does not operate on tachocline shear

- open questions:
  - thermodynamics of field @ base CZ
  - the ‘turbulent diffusion step’ (‘annealing’)
- an effect of quiet Sun flux on TSI ??

Other examples of field generation operating on magnetically driven instabilities

1 Magnetorotational ('MRI') field generation
in accretion disks
2 Field generation in stably stratified zones of stars

1: - Angular momentum distribution in a Keplerian disk
$j \sim r^{1/2}$ hydrodynamically stable
- seed field unstable to growth of magnetorotational
- B breaks a hydrodynamic constraint:
'magnetically enabled' shear instability
- flows are *consequence* of B, not its source

Field generation in a stably stratified stellar interior

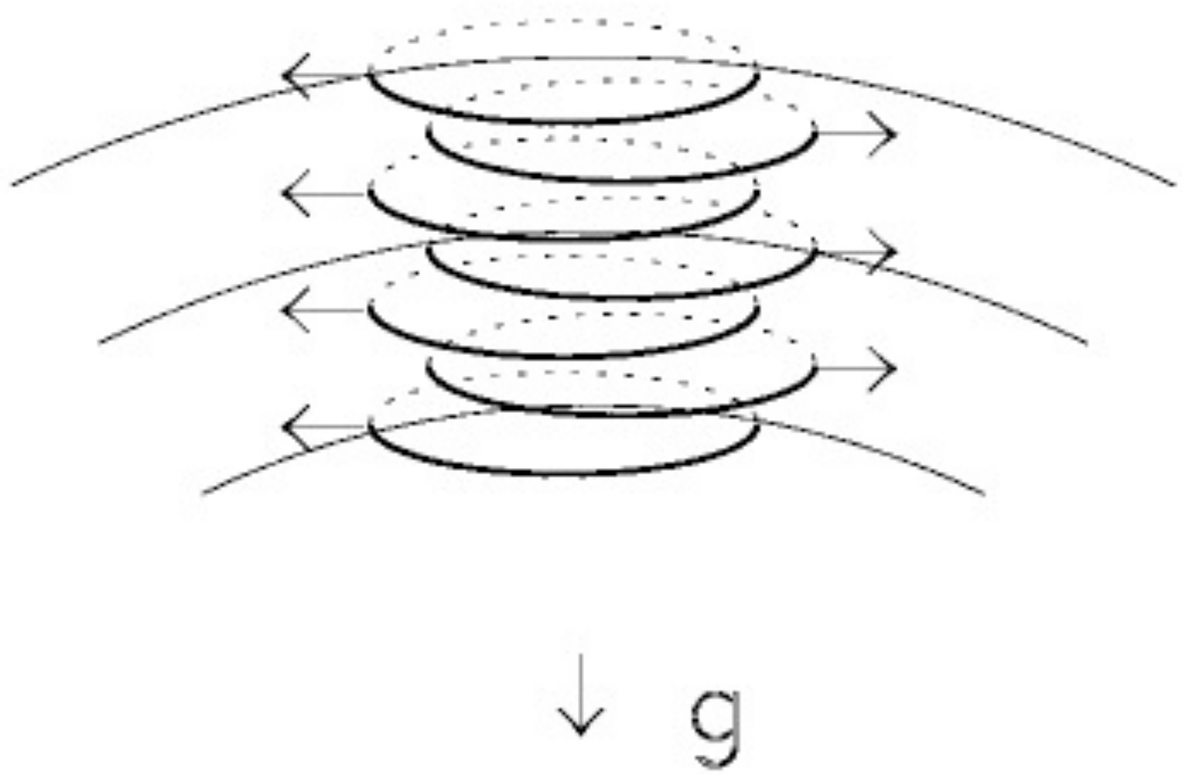
Energy source: differential rotation from
- spindown by stellar wind torque,

or
- change of internal structure by stellar evolution

field amplification cycle:
- seed field $B_{\rm p}$
- field line stretching by $\Omega(r)$, → $B_\phi \sim t$
- instability driven by magnetic energy sets in,
- v_r acting on B_ϕ→ new $B_{\rm p}$

which instability?
- pinch type inst.
- magnetic buoyancy
- magnetorotational (MRI)

First to set in: an m=1 pinch type instability.
'Tayler inst.' (R.J. Tayler 1956 ... 1980 ...1986)



Stable stratification dominates dynamics

Radial length scale $\frac{l_r}{r} \approx \omega_A^2/N^2 = \frac{v_A^2}{r^2 N^2} \ll 1$

horizontal $l \sim r$

Need to include: thermal diffusion, magnetic diffusion

Instability conditions from Acheson's (1978) dispersion relation for azimuthal fields in stars

Simple model for a field amplification cycle: (HCS 2002)

- 'shellular' rotation $\Omega(r)$
- ignore θ - dependence of inst.
- $e = \pi = 2 = 1$

$\longrightarrow$

Solar interior ($\Delta\Omega/\Omega \sim 0.05$)
- field amplification 10-100 x critical
- magnetic stress sufficient to keep up with spindown torque

(Schüssler et al. 1994)

- Field generation can happen in a global, hydrodynamically stable velocity field
- Closing of amplification cycle possible by different forms of magnetic instability:
  - in solar convection zone: magnetic buoyancy
  - in accretion disks: MRI, buoyancy

  in convectively stable zones of ✶✶: Tayler inst.

- nearly uniform rotation solar interior due to a (weak form of) dynamo action